Charles M. Lieber
Department of Chemistry, Harvard University
12 Oxford Street, Cambridge, MA 02138

Personal Data

Date and Place of Birth: April 9, 1959; Philadelphia, PA

Academic Training

Undergraduate:	B.A. in Chemistry, Franklin and Marshall College, 1981
Graduate:	Ph.D. in Chemistry, Stanford University, 1985
Postgraduate:	Postdoctoral Research, California Institute of Technology, 1985-1987

Professional Experience

1987-1990, Assistant Professor of Chemistry, Columbia University
1990-1991, Associate Professor of Chemistry, Columbia University
1991-present, Professor of Chemistry, Harvard University

Academic and Professional Awards

Fellow of The American Association for the Advancement of Science (1997); Fellow of The American Physical Society (1996); Creativity Award, National Science Foundation (1996); Leo Hendrik Baekeland Award, American Chemical Society (1995); George Ledlie Prize, Harvard University (1994-1995); 3M Lecturer in Materials Science, University of British Columbia, (1994), Merck Lecturer, Franklin and Marshall College (1994); Materials Research Society Outstanding Young Investigator Award (1993); ACS Pure Chemistry Award (1992); Dinkewalter Prize (1992); Camille and Henry Dreyfus Teacher-Scholar Award (1990-1995); Wilson Prize (1990); Alfred P. Sloan Fellowship (1990-1992); David and Lucile Packard Fellowship (1988-1993); Presidential Young Investigator Award (1988-1993); Distinguished New Faculty Award, Dreyfus Foundation (1987); NIH Postdoctoral Research Fellow (1985-1987); Joseph W. Richards Fellow of the Electrochemical Society (1985); B.A. degree, Magna Cum Laude, with Honors in Chemistry (1981); American Institute of Chemists Distinguished Senior Award (1981); Theodore Saulnier Research Award (1981); Pentathalon Medal, for Excellence in Chemistry (1981); Phi Beta Kappa (Elected 1981)

Professional Society Membership

American Chemical Society
American Physical Society
American Association for the Advancement of Science
Materials Research Society

Editorial and Advisory Boards

Advanced Materials
Chemistry: A European Journal
Chemistry of Materials
International Union of Pure and Applied Chemistry

Research Interests

Chemistry and physics of materials. Relationships between atomic structure and physical properties in low-dimensional and nanoscale materials. Rational synthesis of new materials and nanostructured solids. Chemical force microscopy and determination of intermolecular interactions in inorganic, organic and biological systems.

Towards the Carbon Computer

Charles M. Lieber
Harvard University
Cambridge, MA 02138

Overview of Presentation

- Introduction
  - status of Si-based computing
  - potential DoD needs
- Molecular Electronics
  - concept and key advantages
  - critical issues
- Carbon Nanotube Molecular Computer
  - key features of carbon nanotubes
  - underlying ideas for electronics
  - design analysis
  - approaches to fabrication
  - expected performance
- Conclusions

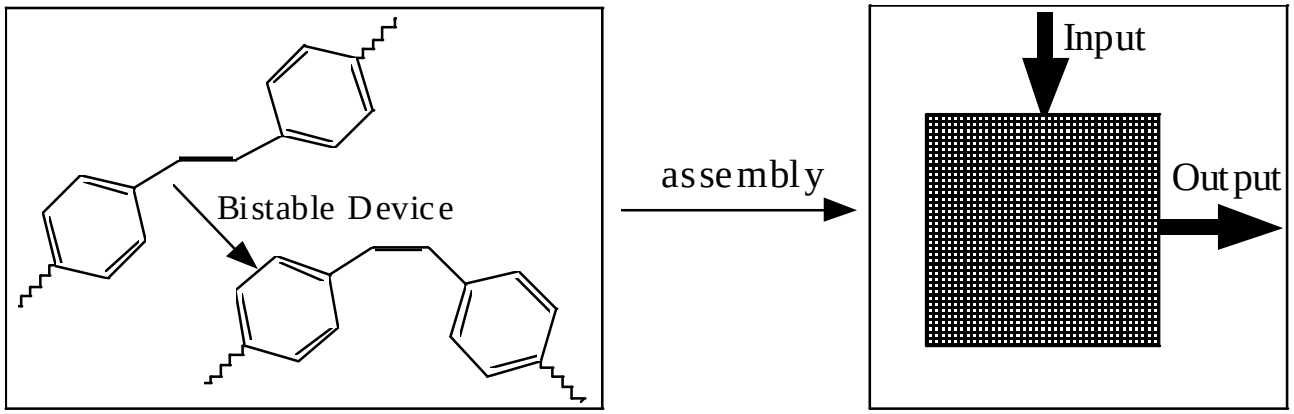
Silicon Based Electronics

It is expected that the exponential growth in Si-based computing power will come to an end about 2010 due to both fundamental and economic reasons:

- fundamental physical limitations will be reached for device elements and wire interconnects that prevent reliable function of present designs.
- the concurrent exponential cost in FAB lines with decreasing feature size will make it uneconomical to consider further integration (in Si).

Molecular Electronics

- Molecular based electronics can overcome the fundamental physical and economic issues limiting Si technology.
- First, it is physically possible to have single molecule devices.
- Second, massively parallel organization of molecular or nanoscale elements can be achieved (cheaply) by self-assembly and chemical synthesis.



Molecular Electronics: Critical Issues

- What systems can be used to address large numbers of molecular devices, and how can these be organized into high-density two and three-dimensional arrays?
- What device types can provide bistable operation and how can these be connected in large number to input/output lines?
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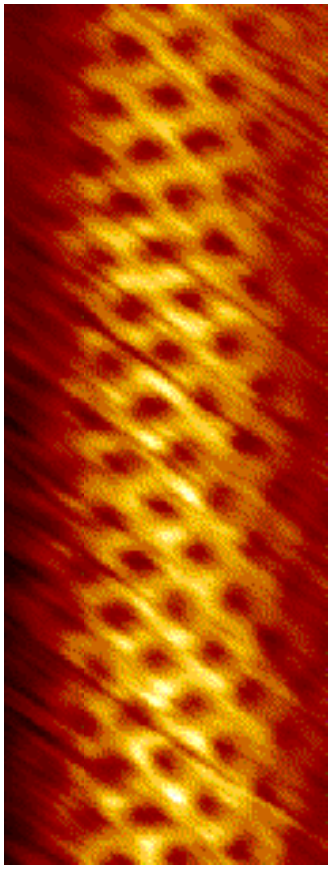
These critical challenges can be overcome using carbon nanotube based electronics!

Why Carbon Nanotubes?

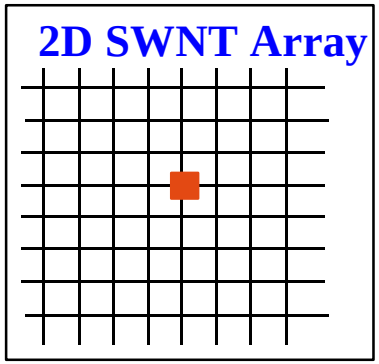
Single-walled carbon nanotubes possess critical features needed for molecular electronics:

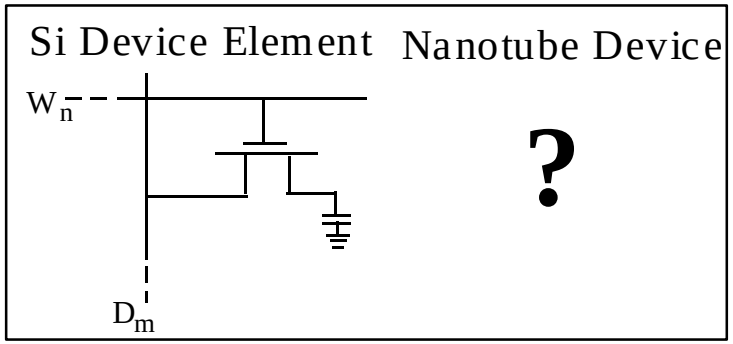
- molecular-scale wires of atomic perfection ⇒ input/output; integration at 10^{12} (2D) and $>10^{15}$ (3D)
- controllable chemical properties ⇒ assembly; synthesis of devices
- stiffest and toughest known material ⇒ small devices can be robust; potential molecular MEMs



Nanotube Molecular Electronics

- SWNT molecular wires can be organized into 2D arrays analogous to, for example, word/bit lines in silicon memory devices.
- At each junction or cross, a device must be created. In a Si-DRAM, the device consists of a transistor and capacitor. What can be created for nanotubes?



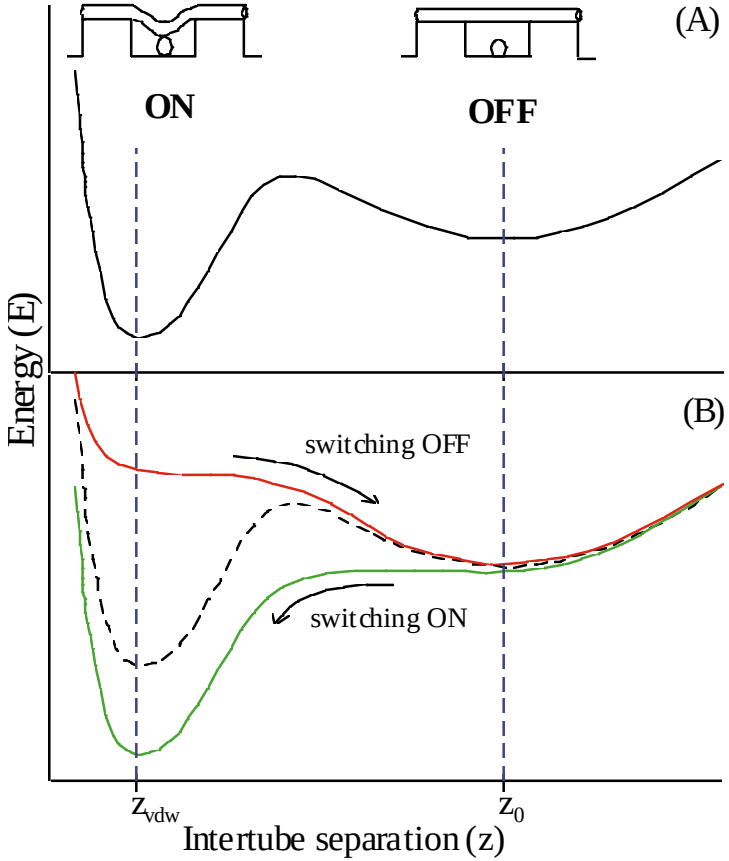


Nanotube Device Concept

A conceptually simple bistable device can be achieved for a suspended crossed nanotube geometry:

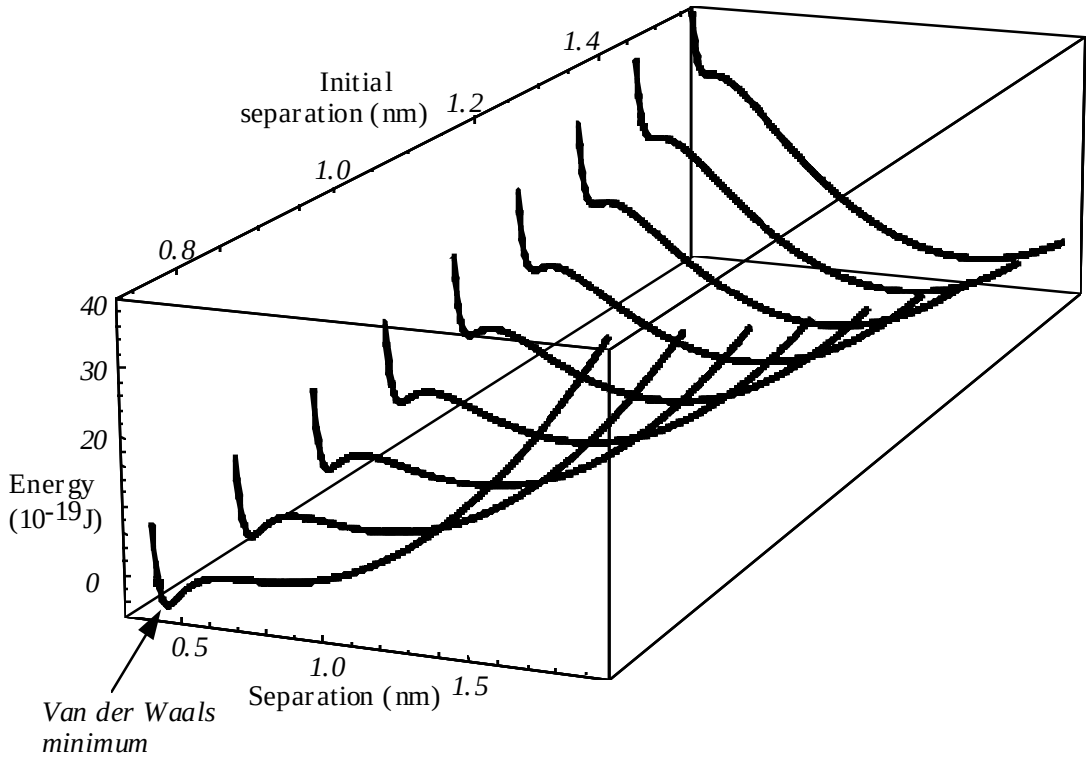
- the OFF state corresponds to mechanical equilibrium
- the ON state corresponds to Van der Waals contact
- switching can be achieved electrostatically by biasing the nanotubes (e.g., +/- or +/+).
- the static potential and switching voltages can be determined by evaluating the total energy:

$$E_T = E_{elast} + E_{VdW} + E_{elec}$$



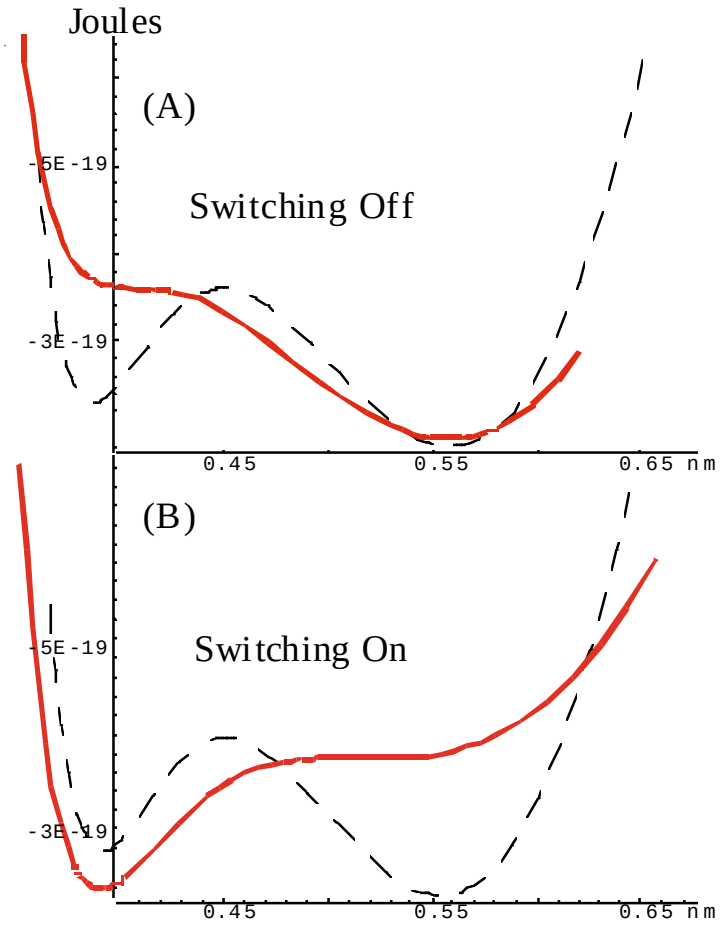
Design Analysis: Static Potential

- Device bistability can be evaluated by analyzing the static potential for the crossed nanotube geometry.
- For a length between suspension points of 15 nm, two well-defined minima (i.e., bistable) are observed for separations of 0.85 to 1.45 nm.



Design Analysis: Device Switching

- The switching threshold for the nanotube device is determined by evaluating the electrostatic contribution to the total energy: $E_T = E_{elast} + E_{VdW} + E_{elec}$
- Switching off is done by biasing the crossing nanotubes with the same polarity (repulsive), so that they move toward mechanical equilibrium. Switching on is done by biasing with opposite polarity, so that they are attracted toward a stable van der Waals contact.
- A switching threshold of 4-5 V is achievable.



Nanotube Electronics: Performance

- Device Integration Levels
  - * $10^{12}/cm^2$ in 2D
  - * $> 10^{15}/cm^3$ in 3D
- Operating Speed (RC)
  - * at least 10-100 GHz
- Power Requirements
  - * < 4μW average power (vs. >100 mW for Si DRAM)